

Synthesis and fluorescence enhancement of oligophenylene-substituted calix[4]arene assemblies†

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Tetra-oligophenylene substituted calix[4]arene assemblies containing up to three phenylene units have been synthesized by a convergent approach using Suzuki cross-coupling and their optical properties were investigated and compared with the corresponding monomer.

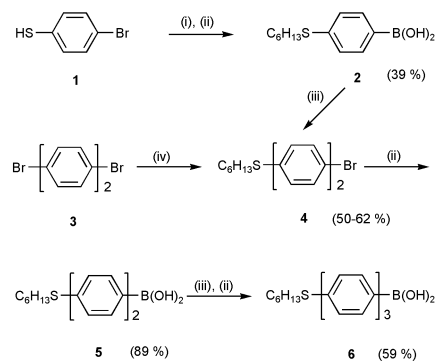
Calixarenes¹ have been widely exploited as supramolecular building blocks for molecular encapsulation^{2,3} as well as ion recognition and sensing⁴ in the last decade. Recently, it has been of great interest to extend the rigid cavity at the upper rim of calixarenes for expanded cavity receptors⁵ as they are beneficial to the encapsulation and recognition properties. In addition, the use of calix[4]arene as the pre-defined and pre-organized framework to incorporate with extended chromophores for intramolecular electronic transfer⁶ and inter-chromophoric interaction investigations^{7,8} has drawn some attention. As a result, there are considerable synthetic effort to expand the rigid cavity at the upper rim of calix[4]arenes. We are particularly interested in synthesizing oligophenylene substituted calixarene assemblies for functional property investigations as the highly extended styrylstyrylcalix[4]arene derivatives show poor photostability in solution which is presumably due to the photo-dimerization of the proximate co-facial vinyl units.

Several methods have been developed to prepare *p*-phenylcalix[4]arene;⁹ however, these procedures afford very low yields. On the other hand, *p*-phenylcalix[4]arene tetraalkyl ethers are easily synthesized in good yields by various metal catalysed cross-coupling protocols, which include Suzuki-type coupling,^{10,11} and Negishi-type coupling.¹² Nevertheless, there is a lack of example or methodology of synthesizing longer homologues of oligophenylene substituted calix[4]arenes reported so far. To this end, we report herein a facile protocol to synthesize an homologues series of tetra-oligophenylene substituted calix[4]arene assemblies containing up to three phenylene units end-capped with alkylsulfanyl donating substituents, **9a–c** and with alkylsulfanyl withdrawing substituents, **10a–c**. In addition, their optical properties were characterized and compared with the corresponding monomer.

We found that Suzuki cross coupling was particularly versatile for the convergent synthesis of the homologues series of oligophenylene-substituted calix[4]arene assemblies as good reactivity and regioselectivity could be obtained by various catalytic palladium compounds/complexes. Cross coupling of oligoarylboronic acid and tetrahalocalix[4]arene tetraalkyl ether was used as a key step to construct the highly extended cone-conformed assemblies. The syntheses of (oligo-)arylboronic acids are summarized in Scheme 1. Alkylation of 4-bromophenol **1** with 1-bromohexane in basic medium afforded 1-bromo-4-hexylsulfanylbenzene in excellent yield (97%). Lithium bromide exchange of the bromine at $-78\text{ }^{\circ}\text{C}$ followed by quenching with trimethyl borate at room temperature and subsequent acid hydrolysis afforded 4-hexylsulfanylbenzeneboronic acid **2**. 4-Bromo-4'-hexylsulfanylbiphenyl **4** was prepared either by regioselective Suzuki cross-coupling of

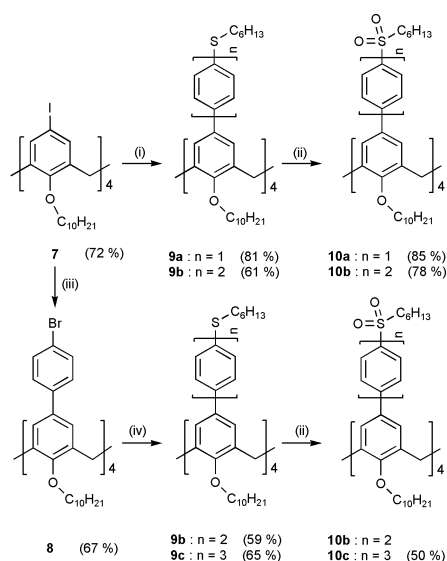
1-bromo-4-iodobenzene with **2** (50%) or by nucleophilic aromatic substitution of 4,4'-dibromobiphenyl **3** with 1-hexanethiol in the presence of NaOH in DMF (62%). Subsequent conversion of bromide to boronic acid functionalities afforded 4'-hexylsulfanyl-4-biphenylboronic acid **5** in a good yield. Hexylsulfanyl-substituted terphenylboronic acid **6** was prepared accordingly using the same stepwise approach as described above starting with the two-phenyl-ring boronic acid **5**.

Tetraiodocalix[4]arene tetradecyl ether **7** was prepared according to the procedures published in the literature.¹³ Cross-coupling of **7** with boronic acid **2** or **5** in the presence of a catalytic amount of Pd(OAc)₂-2P(*o*-tol)₃ complex afforded the corresponding tetraoligophenylene substituted calix[4]arene assemblies **9a** or **9b**, respectively, in good yields (Scheme 2). It should be stated that the Pd(OAc)₂-2P(*o*-tol)₃ complex is found to be more efficient than the classical Pd(PPh₃)₄ as a catalyst for the cross-coupling and the coupling reaction also worked well with tetrabromocalix[4]arene tetradecyl ether but required more drastic conditions. However, the reaction of tetraiodocalix[4]arene **7** with terphenylboronic acid **6** could not be driven to completion which is presumably due to the increased steric crowdedness of the calix[4]arene reaction sites created by the assembled oligophenylene units particularly in the construction of the higher homologues of an assembly. To alleviate the crowdedness of the calix[4]arene reaction sites, the extended tetrabromophenylcalix[4]arene tetradecyl ether **8** was pursued and prepared by selective cross-coupling of commercially available bromophenylboronic acid and **7** using Pd(PPh₃)₄ as a catalyst. It is important to note that the use of Pd(OAc)₂-2P(*o*-tol)₃ the complex as a catalyst in this reaction afforded no desired product. Cross coupling of **8** and biphenylboronic acid **5** under typical conditions afforded **9c** in a moderate yield. (Scheme 2). Besides, assembly **9b** can be prepared by coupling of **8** with boronic acid **2**. The MALDI-TOF mass spectra of **9b** and **9c** showed a major peak at *m/z* 2081 and 2385, respectively, corresponding to [M + H + Na]⁺. MCPBA-oxidation of alkylsulfanyl-substituted calix[4]arene assemblies, **9a–c** in CH₂Cl₂ afforded the corresponding alkylsulfanyl-substituted calix[4]ar-



Scheme 1 Reagents and conditions: (i) C₆H₁₃Br, NaH, DMF, 70 °C, overnight; (ii) a, BuⁿLi, THF, $-78\text{ }^{\circ}\text{C}$, 1 h. b, B(OMe)₃, $-78\text{ }^{\circ}\text{C}$ to rt, 1 h. c, H⁺; (iii) IC₆H₄Br, 5 mol% Pd(OAc)₂-2P(*o*-tol)₃, K₂CO₃, toluene, 50 °C, 6 h; (iv) C₆H₁₃SH, NaOH, DMF, 150 °C.

† Electronic supplementary information (ESI) available: experimental procedures and spectral data of all new compounds. See <http://www.rsc.org/suppdata/cc/b2/b210493h/>



Scheme 2 Reagents and conditions: (i) $C_6H_{13}S(C_6H_4)_nB(OH)_2$, 40 mol% $Pd(OAc)_2-2P(o-tol)_3$, K_2CO_3 , toluene, 50 °C, 6 h; (ii) MCPBA, CH_2Cl_2 , 0 °C, 1 h; (iii) $BrC_6H_4B(OH)_2$, 40 mol% $Pd(PPh_3)_4$, K_2CO_3 , toluene, 45 °C, overnight; (iv) $C_6H_{13}S(C_6H_4)_{n-1}B(OH)_2$, 40 mol% $Pd(OAc)_2-2P(o-tol)_3$, K_2CO_3 , toluene, 50 °C, 6 h.

ene assemblies, **10a–c**, respectively in moderate to good yields. The MALDI-TOF mass spectra of **10b** and **10c** showed a major peak at 2210 corresponding to $[M + 2H + Na]^+$ and 2512 corresponding to $[M + Na]^+$, respectively. In addition to low/high resolution mass spectroscopy, all the newly synthesized assemblies were characterized with 1H NMR and ^{13}C NMR and found to be in good agreement with expected structures.[†]

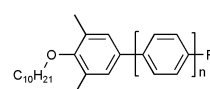
For comparison, the corresponding monomers **11a–c** and **12a–c** were also synthesized using the same convergent approach. Dependent on the nature of substituents end-capped on the oligophenylene skeletons, the optical properties of the assemblies vary differently with respect to the corresponding monomer. Even though the spectral features of the assemblies and the corresponding monomer are similar, the assemblies **9a–c** bearing hexylsulfanyl donating groups exhibit a slightly blue shift in the absorption maxima, λ_{max} and the assemblies bearing hexylsulfanyl withdrawing groups **10a–c** consistently exhibit red shift relative to the corresponding monomer (Table 1) This suggest that oligophenylenes built onto the calix[4]arene

Table 1 Summaries of physical measurements of **9a–c**, **10a–c**, **11a–c** and **12a–c**

Compound	λ_{max}^{abs} ^{a/} nm	$10^4\epsilon_{max}^a$ $M^{-1} cm^{-1}$	λ_{max}^{em} ^{a/} /nm	$\Phi_{FL}^{a,b}$	$\tau/ns^{a,c}$
9a	283	10.12	379		0.82
9b	301	14.89	384	0.12	0.84
9c	312	22.65	386/398	0.31	0.85
10a	284	6.99	373		1.02
10b	303	11.04	412	0.77	1.03
10c	313	15.26	427	0.74	1.01
11a	287	2.37	372		0.76
11b	307	3.47	375	0.28	0.78
11c	315	5.07	379/390	0.51	0.80
12a	282	1.91	366		1.34
12b	302	3.22	405	0.70	1.38
12c	312	4.23	414	0.60	1.37

^a Measured in $CHCl_3$. ^b Average of two independent measurements and using quinine in 1 M H_2SO_4 ($\Phi_{313} = 0.48$ at 313 nm) as a standard. ^c Using nitrogen laser as an excitation source.

framework show little interaction in the ground-state. In contrast to the absorption behaviour, the red shift of the emission maxima of the assemblies are substantial in both series as compared to those of the corresponding monomer. This implies that the excited state chromophoric interaction within an assembly is significant. On the other hand, the excitonic interaction only affects the fluorescence lifetimes (τ) of the assemblies in a lesser extent relative to the corresponding monomer. For the hexylsulfanyl end-functionalized assemblies **9b,c**, the fluorescence quantum yields (Φ_{FL}) are found to be substantially lower than that of the corresponding monomer **11b,c**. It is consistent to the general observations that ordered packing/arrangement of the emissive molecules or polymers often leads to excimers formation and then fluorescence quenching. However, the hexylsulfanyl end-functionalized assemblies **10b,c** consistently exhibit larger fluorescence quantum yields than that of the corresponding monomer **12b,c**. This result implies that acentric arrangements of donor–acceptor fluorophores will lead to fluorescence enhancement.



11a: n = 1, R = SC_6H_{13} **12a**: n = 1, R = $SO_2C_6H_{13}$
11b: n = 2, R = SC_6H_{13} **12b**: n = 2, R = $SO_2C_6H_{13}$
11c: n = 3, R = SC_6H_{13} **12c**: n = 3, R = $SO_2C_6H_{13}$

In summary, we have developed a convergent approach using Suzuki cross-coupling reaction to synthesize novel series of highly extended tetra-oligophenylene substituted calix[4]arene assemblies containing up to three phenylene units end-capped with hexylsulfanyl donating groups or hexylsulfanyl withdrawing groups. We have also found that, in contrast to the electron-donor substituted assemblies, the hexylsulfanyl end-functionalized assemblies exhibit fluorescence enhancement as compared to the corresponding monomers. These findings may provide a new avenue to design fluorophores and emissive materials for luminescence applications.

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